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The US JGOFS Synthesis and Modeling Project – An introduction

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Abstract

The field data collected as part of the international Joint Global Ocean Flux Study (JGOFS) provide an unprecedented view of marine biogeochemistry and the ocean carbon cycle. Following the completion of a series of regional process studies, a global CO_2 survey, and a decade of sampling at two open-ocean time-series, US JGOFS initiated in 1997 a final research phase, the Synthesis and Modeling Project (SMP). The objective of the US JGOFS SMP is to "synthesize knowledge gained from the US JGOFS and related studies into a set of models that reflect our current understanding of the oceanic carbon cycle". Here we present an overview of the SMP and highlight the early scientific results from the project.

1. Introduction

The stated goals of the international Joint Global Ocean Flux Study (JGOFS) are to (1) determine the processes that control the partitioning of carbon and related biologically active substances within the ocean and between the ocean and atmosphere, and (2) develop a capability to predict how changes in the environment will influence this partitioning (JGOFS, 1990).

To reach these goals, the US JGOFS program initiated an extensive series of marine biogeochemical field studies over the last decade. The resulting data sets from two long-term time series near Hawaii (Karl and Lukas, 1996) and Bermuda (Michaels and Knap, 1996), a joint JGOFS/WOCE global CO_2 survey (Wallace, 2001), and regional process studies in the North Atlantic (Ducklow and Harris, 1993), Equatorial Pacific (Murray et al., 1995), Arabian Sea

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(Smith et al., 1998), and Southern Ocean (Smith et al., 2000) offer an unprecedented view of the ocean carbon system. The bulk of these observations are presently available to the community through innovative, web-based databases maintained by the US JGOFS Data Management Office (http://usjgofs.whoi.edu), the two time-series (http://www.bbsr.edu/cintoo/bats/bats.html and http://hahana.soest.hawaii.edu/hot/hot_jgofs.html), and the WOCE Hydrographic Program Office (http://whpo.ucsd.edu).

Following the end of the Southern Ocean process study in 1998, US JGOFS moved into its final phase with the Synthesis and Modeling Project (SMP). The SMP arose out of recognition that attaining the two central JGOFS aims required a dedicated, comprehensive effort to synthesize and model the JGOFS field data beyond the efforts of individual PIs and specific projects. The final legacy of the US JGOFS program will include the high-quality field data, data synthesis products, and a set of conceptual process models and integrated regional and global numerical simulations that encapsulate our improved understanding of the marine carbon cycle (Fig. 1).

An SMP Implementation Plan (US JGOFS, 1997) was written with wide participation from JGOFS researchers and other oceanographers who attended a planning meeting in the summer of 1996 at Durham, NH. The program's scope as defined in the plan is to

> "synthesize knowledge gained from the US JGOFS and related studies into a set of models that reflect our current understanding of the oceanic carbon cycle"

The SMP's main focus is on processes that control carbon partitioning within oceanic reservoirs and between the ocean and atmosphere. Five more specific objectives are presented in the implementation plan.

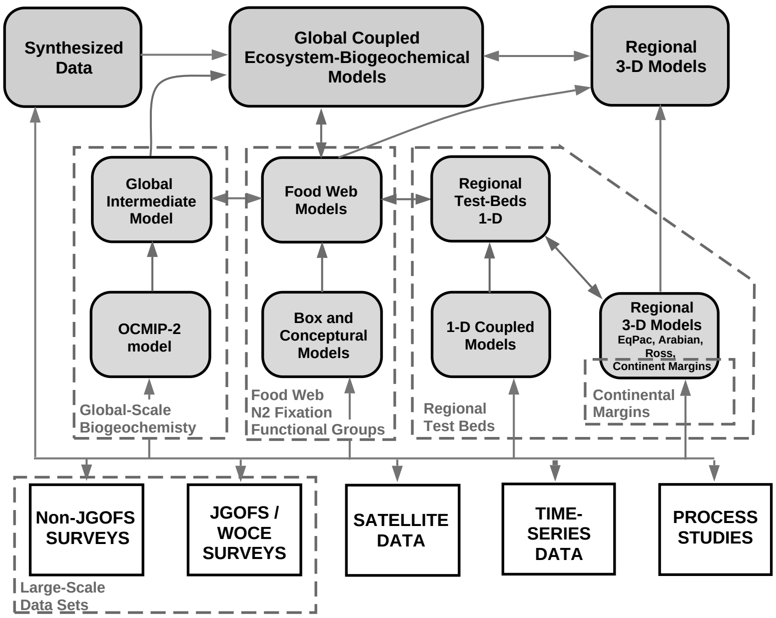

Fig. 1. Schematic of SMP components and working group structure.

- To synthesize our knowledge of inorganic and organic carbon fluxes and inventories, both natural and anthropogenic.
- To identify and quantify the principal processes that control the partitioning of carbon among oceanic reservoirs and between the ocean and atmosphere on local and regional scales, with a view towards synthesis and prediction on a global scale.
- To determine the mechanisms responsible for spatial and temporal variability in biogeochemical processes that control partitioning of carbon among oceanic reservoirs and between the ocean and atmosphere.
- To assess and implement strategies for scaling data and models to seasonal, annual, and interannual time scales and to regional and global spatial scales.
- To improve our ability to monitor and predict the role of oceanic processes in determining current and future partitionings of carbon between the ocean and atmosphere, and to evaluate uncertainties and identify gaps in our knowledge of these processes.

Close linkages between modeling and data analysis activities are clearly required. Practical biogeochemical models should be grounded in and thoroughly evaluated against field observations; and data synthesis should be directed toward addressing the known issues of current models (e.g., identifying critical or missing mechanisms; constraining new conceptual process models and parameterizations).

The overall success of the SMP depends heavily on fostering strong interactions between the observational and modeling communities and focusing those efforts in a coordinated fashion. One straightforward solution adopted within SMP is to encourage collaborative projects by groups of scientists with expertise on both field data and modeling. It was recognized, however, that the overall synthesis and modeling objectives—to develop models that skillfully replicate the dynamics of the ocean carbon cycle at present and into the future—required a directed, community effort and synergy at a level above that of individual grants.

These organizational needs are explicitly dealt with through the creation of a centralized coordination or management team (Doney, Sarmiento, and Kleypas), annual principal investigator meetings, scientific working groups (Fig. 1), and focused workshops directly targeted at specific research topics. The synergy generated through the various SMP meetings is evident by the rise of cross-project activities within the working groups. The SMP maintains a comprehensive internet site (http://usjgofs.whoi.edu/mzweb/syn-mod.htm) and has published a set of meeting reports on biogeochemical time-series (Doney and Sarmiento, 1998), climate change response (Doney and Sarmiento, 1999), phytoplankton functional groups (Falkowski, 1999), nitrogen fixation (Hood et al., 2000a,b), Equatorial Pacific modeling (Hofmann et al., 2000), and continental margins (Muller-Karger, 2000).

One innovative aspect of the SMP is the formalization of a "model-data" policy, requiring the public release of synthetic data products, model code and solutions generated under SMP funding. The model-data policy approximately mirrors the data policy for the field components of US JGOFS. Because of the often large size of numerical model output, a pilot web-based Live Access Server (LAS) (http://usjgofs.whoi.edu/las/) data visualization and sub-sampling system has also been created (Hankin et al., 1998). Finally, to facilitate the use of US and International JGOFS data in modeling applications, many of the time-series and process study data have been assimilated into uniform formats with standardized units (Kleypas and Doney, 2001).

This *Deep-Sea Research II* special issue brings together a series of research papers resulting from the first phase of the SMP. Here we highlight the early scientific results from the project.

2. Science background

Growing concern over the issue of climate change has focused efforts on understanding the temporal evolution, climate impact, and potential feedbacks for biogeochemical forcing factors such as radiatively active trace gas species (e.g., CO_2, CH_4, N_2O), natural and anthropogenic aerosols, and land-use change (Schimel et al., 1995, 1996). With recent improvements in numerical climate models and a general convergence in estimated climate sensitivities, the future levels of atmospheric greenhouse species such as CO_2 have become one of the major uncertainties associated with climate predictions through the next few centuries (Hansen et al., 1998). Because the ocean is a major reservoir for the uptake and storage of anthropogenic CO_2 on decadal to centennial timescales (Schimel et al., 1995), emphasis on the marine carbon cycle and its interactions with the terrestrial and atmospheric carbon reservoirs is clearly warranted (Sarmiento and Wofsy, 1999).

Oceanic uptake of anthropogenic carbon for the early 1990s is estimated from a variety of methods to be approximately 2 Pg C yr^{-1}, or roughly a third of the atmospheric fossil fuel emissions (e.g., Rayner et al., 1999; Prentice et al., 2001). Model projections are that the ocean will continue to draw down significantly excess atmospheric carbon dioxide over the next several centuries (e.g., Sarmiento et al., 1995), but the magnitude is sensitive to the responses of ocean physics and biota to climate change (e.g., Sarmiento et al., 1998; Matear and Hirst, 1999; Bopp et al., 2001). The range of biological responses to future climate change is typically poorly characterized (Denman et al., 1996) and includes direct physiological effects (e.g., temperature, pH, CO_3^{-2}), ecosystem level effects due to changing ocean circulation (e.g., nutrient supply, primary and export production, community structure), and effects due to alterations in other external forcings (e.g., modifications to atmospheric dust deposition and thus Fe inputs) (Doney and Sarmiento, 1999).

Simple marine ecosystem models have been used extensively in oceanography since the early 1970s (Steele, 1974), but have roots much further back in the literature (Riley, 1946; Steele, 1958). The area was revitalized about the time of the inception of JGOFS by the seminal work of Evans and Parslow (1985), Frost (1987), Fasham et al. (1990), and Moloney and Field (1991). A wide range of mixed-layer and one-dimensional model variants have been constructed over the last decade, covering biogeographical regimes from oligotrophic subtropical gyres (e.g., Doney et al., 1996) to classic seasonally mesotrophic spring blooms (e.g., Fasham, 1995) and subarctic high-nitrate, low chlorophyll (HNLC) regions (e.g., McClain et al., 1996). The early ecosystem models, largely based on simple PZND (phytoplankton, zooplankton, nutrient, detritus) dynamics, are gradually being modified to capture the greater range of the ecological complexity observed in the ocean. Mixed-layer and 1-D models, while providing a useful framework or test-bed for exploring ecological processes and implementing biological data assimilation techniques, however, often are developed and evaluated for a single site; the generality of these models and their derived parameter values for basin and global simulations remain open questions.

Early three-dimensional basin and global scale calculations (e.g., Sarmiento et al., 1993; Six and Maier-Reimer, 1996) also were conducted with single, uniform PZND ecosystem models applied across the entire domain. These experiments demonstrated that large-scale features, such as the contrast between the oligotrophic subtropical and eutrophic subpolar gyres, could be simulated qualitatively. Some problems arose, however, with the details. For example, the incorporation of the Fasham et al. (1990) model into a North Atlantic circulation model by Sarmiento et al. (1993) showed too low production and biomass in the oligotrophic subtropics and too weak a spring bloom at high latitudes. The Six and Maier-Reimer (1996) result required careful tuning of the phytoplankton growth temperature sensitivity and zooplankton grazing in order to control biomass in the Southern Ocean HNLC. A number of coupled 3-D ecosystem models now exist for regional (Chai et al., 1996; McCreary et al., 1996; Dutkiewicz et al., 2001) and global (Aumont et al., 2001) applications, and these 3-D ecosystem models are beginning to include many of the features addressed in 1-D. As outlined in Doney (1999), the pressing modeling issues include: food-web dynamics, multi-element limitation, and community structure; coupling biogeochemistry with large-scale physical circulation; mesoscale biological-physical interactions; air–sea, land–ocean, and coastal–open ocean exchange; and model-data evaluation and data assimilation.

This review paper also stresses a key point:

> "Biogeochemical modeling is inherently data driven, and the major challenge (and opportunity) for the next decade is to integrate modeling efforts with the growing body of observations and emerging conceptual paradigms from large-scale field and satellite programs such as the Joint Global Ocean Flux Study (JGOFS), Global Ocean Ecosystems Dynamics (GLOBEC), Coastal Ocean Processes (CoOP), World Ocean Circulation Experiment (WOCE), IronEx, Sea-viewing Wide Field-of-view Sensor (SeaWiFS), and the Earth Observing System (EOS)". (Doney, 1999)

The US JGOFS Synthesis and Modeling Project is directly addressing this need for improved interaction among the field study, data synthesis and modeling aspects of ocean biogeochemical research.

3. Overview of project results

More than 100 investigators are now involved in the Synthesis and Modeling Project (Table 1), within some 50 projects supported by funding from the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the Department of Energy (DOE). These projects include both synthesis and modeling studies, at spatial scales from local marine ecosystems (and 1-D models) to global-scale carbon cycle (and 3-D circulation models). Fig. 2 provides a schematic of SMP projects in terms of biogeochemical processes (e.g., surface primary production and export; subsurface transport and remineralization; sediments), while Fig. 3 illustrates their geographic distribution (e.g., regional synthesis and modeling of specific JGOFS process studies, time-series station, or ocean basins; analyses of JGOFS/WOCE global CO_2 survey data; global 3-D models).

This special issue is the first collection of papers derived from efforts within the Synthesis and Modeling Project, although a number of papers based on SMP work have been published prior to this issue as individual contributions. Reflecting the very nature of SMP, these papers offer a

Table 1
List of US JGOFS Synthesis and Modeling projects, lead principal investigators of each, and major characteristics of each study

Investigator(s)	Project	Scale[a]	Synth[b]	Model[c]	Proc[d]	Sat
Arrigo, Robinson	Coupled ice-ocean model of mesoscale phys./biol. interactions	R		3		
Barber et al.	New and export productivity regulation by Si and Fe in equatorial Pacific	R		3	PF	
Bates, Sabine	Temporal variability in global inorganic carbon distributions	G	S		T	
Buesseler	Magnitude, variability and controls of particulate export in the upper ocean	G	SP		ET	
Caldeira	Biological influences on mixed-layer dynamics and global ocean circulation	G		3	T	x
Capone et al.	Modeling N_2 and CO_2 fixation by *Trichodesmium*	G	SP	x	PF	x
Carr, Kearns	Historical and modeling comparison study of four coastal upwelling systems	M	S	x	P	x
Christian, Letelier	Modeling microbial processes and dissolved organic matter at ALOHA	R		3	PF	
Conkright	Assembly, quality control and analysis of CO_2 system	G	S			
Dickson	Synthesis of global surface pCO_2 data	G	S			
Doney	Impact of interannual variability on air-sea CO_2 fluxes and oceanic DIC	G		3	T	
Ducklow et al.	Bacterial biomass and production variability in ocean ecosystems	R	SP	3	B	
Ducklow et al.	Ecosystem structure, biogeochem. fluxes and vulnerability to climate change	R		3		
Falkowski	Representing key phytoplankton groups in ocean carbon cycle models	G	SP	x	F	
Friedrichs et al.	Regional ecosystem model testbeds.	R		13	PFER	
Gardner et al.	Global synthesis of POC using satellite, transmissometer and POC data from JGOFS/WOCE	G	S			x
Glover, Conte	Coupled epipelagic-meso/bathypelagic particle flux model for the BATS/OFP site	R		3	ER	
Gruber	Analyzing/modeling interannual to decadal variability in the carbon cycle of subtropical and subpolar gyres	R		3	T	
Hansell et al.	Mass balance assessments of carbon partitioning	G	SP			
Hofmann	Marine primary productivity in tropical Pacific and Atlantic	R	S	3		
Hofmann et al.	Comparative modeling and data analysis for Ross Sea and W Antarctic Peninsula Regions	R	SP	3		

Table 1 (*continued*)

Investigator(s)	Project	Scale[a]	Synth[b]	Model[c]	Proc[d]	Sat
Honjo et al.	Synthesis of global export and recycling of biogenic material into ocean interior	G	SP		ER	
Hood et al.	Coupled biological/chemical/physical model for Arabian Sea	R		3		
Jackson	Upper-ocean aggregation models for interpreting and predicting carbon fluxes	G		1	FE	
Jackson, Burd	Carbon flows between euphotic zone and 1000 m depth	G	SP	x	FBE	
Jahnke	Deep ocean carbon, carbonate, opal, and nutrient particle fluxes, benthic fluxes and sediment accumulation	G	SP		ERS	
C Keeling	Oceanic carbon cycle model analysis including $\delta^{13}C$ data	G	S			
R Keeling	Southern ocean seasonal net production	R	SP		P	
Key et al.	Redfield remineralization ratios	G	S			
Landry et al.	Data-based models of plankton community structure and export flux	G	SP	x	PF	
Laws	f-ratio model for pelagic marine ecosystems	G	SP		E	
Laws et al.	Adaptive food web model	G		x	FE	
Lee et al.	Degree of saturation state of $CaCO_3$ in the oceans	G	S			
Lizotte, DiTullio	Phytoplankton comm. structure, particulate elemental composition, carbon fixation, bio-optical properties	G	SP		P	
Marshall et al.	Interannual variability of ocean color: synthesis of satellite data and models and participation in OCMIP	G	S	3		x
Martin, Sayles	Organic carbon cycling and $CaCO_3$ in marine sediments: parameterization for global models	G	SP	x	RS	
McClain et al.	Physical-biological interactions in tropical Pacific/Atlantic equatorial surface layers	R	SP	13		x
McGillicuddy	Role of eddies in basin-scale biogeochem. budgets of N Atlantic	R		3	T	
McGillicuddy	Modeling mesoscale biogeochem. processes in a TOPEX/POSEIDON diamond surrounding BATS	R		3	T	x
McGillicuddy	Impacts of mesoscale processes on biogeochem. fluxes in N Atlantic: basins-scale eddy-resolving simulations	R		3	T	
Muller-Karger	Factors influencing carbon fluxes at CARIACO continental margin time series	M	SP	x	PE	x
Murray et al.	Food-web regulation of particulate export flux in HNLC regions	G	SP	1	FE	
Najjar et al.	Evaluation/intercomparison of 3-D marine carbon cycle models	G		3		

Table 1 (*continued*)

Investigator(s)	Project	Scale[a]	Synth[b]	Model[c]	Proc[d]	Sat
Nelson et al.	Si cycling/control of new production and organic carbon export in Southern Ocean and Sargasso Sea	R	SP	x		
Peng et al.	Re-evaluation of Redfield ratios using OACES and DOE/WOCE/JGOFS CO_2 survey data	G	S	x		
Quay, McNichol	Oceanic CO_2 uptake rates from an ocean-wide $^{13}C/^{12}C$-DIC data set	G	S			
Robbins, Dickson	Anthropogenic carbon in the Pacific using diagnostic inverse models of circulation	R	S	3	T	
Roman, Dam	Mechanistic controls of carbon flux by mesozooplankton	R	SP	x	Z	
Sabine et al.	Synthesis and interpretation of the NOAA/DOE global CO_2 survey data	G	S			
Sambrotto, Dickson	Relationship between nitrogen uptake and net community production using JGOFS data and 1-D modeling	R	SP	1	P	
Sarmiento	Oceanic uptake of anthropogenic CO_2 and other trace gases using multiple tracer relationships	G		3	T	
Siegel	Development/application of ocean color models for understanding marine processes at regional/global scales	G	SP	x		x
Talley, Johnson	Estimates of transport and storage of carbon in Pacific using inverse models	R		3	T	
Thompson et al.	Mechanisms controlling the biological pump and CO_2 uptake rates in N Pacific	R		3	T	
Verity	Budgets of biogenic elements in the NW Atlantic ocean margin	M	SP			
Walsh	New sources of NO_3 and N_2 in the S Caribbean: key to CDOC contamination of satellite color signals	R	SP			x
Wanninhkof et al.	Meridional transport of CO_2 in N Atlantic	R	S		T	
Yoder	Large-scale spatial/temporal patterns in chlorophyll a imagery using CZCS, OCTS, POLDER and SeaWiFS	G	S			x

[a] G = global, R = regional, M = continental margin.
[b] S = synthesis, P = parameterization.
[c] 1 = 1d, 3 = 3d, x = general modeling.
[d] P = primary production, Z = zooplankton, F = food web, functional groups, B = bacteria, E = export, R = remineralization, S = sediments, T = transport.

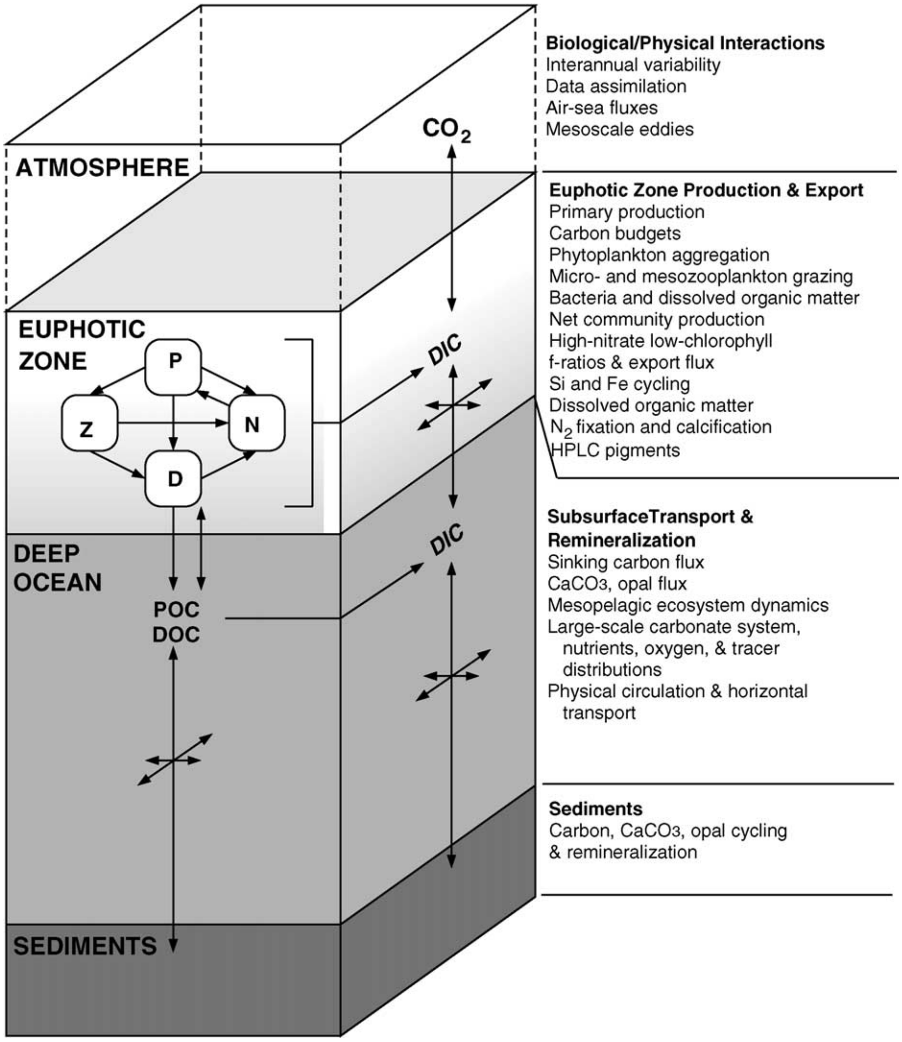

Fig. 2. Physical, ecological and biogeochemical processes included in SMP studies.

broad-based sampling of the many diverse, unresolved issues surrounding the ocean's role in the global carbon cycle. Many papers also reflect the synergism that arises from the sometimes difficult task of integrating synthesis with modeling efforts. The following summary provides a quick-view of this issue's papers in terms of how each fits into the overall goals of the SMP and recent scientific advancements.

3.1. Phytoplankton production and community structure

The factors regulating upper ocean phytoplankton production have received considerable attention within the SMP, with a growing emphasis on multi-nutrient limitation and community

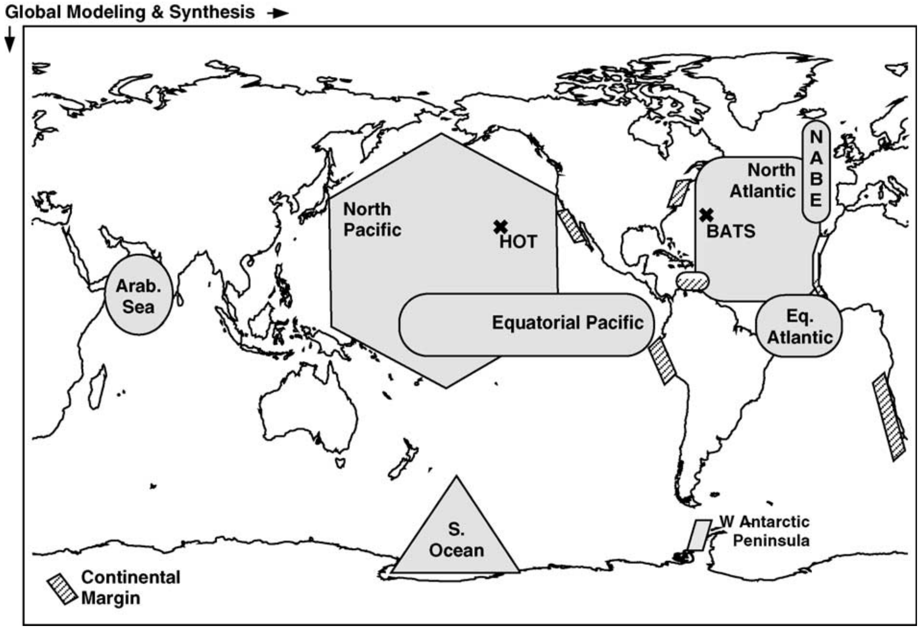

Fig. 3. Geographic distribution of SMP studies.

structure. In-situ iron fertilization studies in the Equatorial Pacific (Coale et al., 1996) and more recently the Southern Ocean (Boyd et al., 2000) provide strong evidence that low ambient iron levels limit production and alter the phytoplankton community structure, favoring picoplankton over larger diatom species, in these high-nitrate low-chlorophyll (HNLC) waters. The effects of iron limitation are now being incorporated either directly or indirectly into box and 1-D ecosystem models for the Equatorial Pacific (Leonard et al., 1999; Friedrichs and Hofmann, 2001; Friedrichs, 2002), subpolar North Pacific (Denman and Pena, 1999), and Southern Ocean (Pondaven et al., 2000) as well as in global simulations (Moore et al., 2002a,b). Iron dynamics have also been included in 3-D basin scale ecosystem models for the tropical Pacific (Chai et al., 1999; Christian et al., 2002a,b).

Aeolian dust deposition is a significant source of iron to much of the ocean euphotic zone, particularly in the Northern Hemisphere, with subsurface sources playing a dominant role only in low atmospheric deposition, upwelling environments such as the HNLC zones of the Equatorial Pacific and Southern Ocean (Archer and Johnson, 2000; Fung et al., 2000). Horizontal advection and subsequent upwelling of iron released from continental margin sediments may also contribute in the Equatorial Pacific (Christian et al., 2002b). The fact that atmospheric Fe fluxes appear to modulate overall ecosystem dynamics in many locations adds a new twist to the original nitrogen based “new production” paradigm of Dugdale and Goering (1967). Dugdale and Wilkerson (1998) suggest that the Equatorial Pacific story is even more complex, with silicate limitation of diatoms, which because of their size and silicious shells often contribute disproportionately to vertical export flux (Buesseler, 1998). Iron-silicate colimitation of diatom growth can also occur (Moore et al., 2002b).

Another trend in the SMP is the evolution beyond simple PZND models, where all species in a trophic level are aggregated into a single box. Now, many ecosystem models include explicit planktonic size and community structure (Armstrong, 1994, 1999; Gregg, 2000,2002; Moore et al., 2002a; Christian et al., 2002a). The ecosystem model of Laws et al. (2000), for example, differentiates low export, high recycling picoplankton-dominated systems from higher export diatom-rich systems. The model predicts that export-ratio (as defined by Buesseler, 1998) varies with primary production and inversely with temperature, and an empirical relationship is developed that, combined with satellite data, can be used to estimate the geographical and temporal export patterns.

The significance of specific phytoplankton functional groups (Falkowski, 1999) is also being recognized, in particular for processes such as nitrogen fixation (Hood et al., 2000b) and calcification (Moore et al., 2002b; Iglesias-Rodríguez et al., 2001) that decouple the traditional carbon and macronutrient cycling. Hood et al. (2001) and Fennel et al. (2002) evaluate different, new parameterizations for *Trichodesmium* nitrogen fixation against field data from the BATS and HOT time-series, respectively. Moore et al. (2002b) include explicit iron limitation on nitrogen fixation, and their simulated global maps of nitrogen fixation agree reasonably well with large-scale in-situ compilations (Capone et al., 1997). Subramaniam et al. (2002) propose a satellite remote-sensing based algorithm for detecting surface *Trichodesmium* blooms using SeaWiFS data, which Hood et al. (2002) apply in estimating spatial and temporal maps of nitrogen fixation rate following existing satellite based primary production techniques (e.g., Behrenfeld and Falkowski, 1997).

The resumption of routine satellite ocean color imaging with OCTS, SeaWiFS and MODIS (e.g., McClain et al., 1998) opens a whole new window for exploring the time and space variability of ocean biology. Carr (2002) uses multi-variable satellite remote sensing data (wind speed, sea surface temperature, ocean color) to characterize the potential productivity of four eastern boundary current regions, with some surprising results. Although she found that primary production estimates for the Benguela Current were about twice those for the Humboldt Current, actual fish catch data for the Benguela were 20 times less. Carr (2002) suggests this difference reflects variations in underlying ecosystem trophic structure and spatial accessibility of the fisheries.

3.2. Zooplankton grazing, export fluxes, and subsurface remineralization

From the perspective of carbon cycle dynamics, the processes removing biomass from the euphotic zone, such as zooplankton grazing and phytoplankton aggregation (Jackson, 2001), are equally important as primary production but are often on less firm mechanistic footing. Roman et al. (2002) address the impact of mesozooplankton at the subtropical, oligotrophic BATS and HOT time-series stations, calculating the mesozooplankton production, ingestion and egestion rates from size-class biomass observations and an empirical temperature/size class regression. While small relative to total annual primary production, mesozooplankton ingestion and potential fecal pellet production are comparable in magnitude to the floating sediment trap estimates of annual export production at both sites, with higher absolute and relative mesozooplankton fluxes at the more physically stable HOT site.

The processes controlling the fate of particulate and dissolved matter export from the surface layer (e.g., remineralization rate, sinking speed, transformation) are critical for determining large-scale ocean biogeochemical distributions (e.g., oxygen, nutrients) and carbon sequestration. Most of these processes are still not well understood mechanistically, but are gaining increasing attention of researchers. For example, Jackson and Burd (2002) describe a predator-prey model of the mesopelagic ecosystem that explicitly accounts for the loss of sinking particle flux due to zooplankton feeding and bacterial degradation. The modeled vertical particle flux decreases either exponentially or inversely with depth, depending on the model variant, roughly comparable with observations. For some model formulations, their theoretical study predicts complex, chaotic variability in subsurface particle fluxes arising from a smooth surface seasonal cycle and the population dynamics of a subsurface particle feeder and its predator.

In terms of sub-euphotic zone remineralization, almost all global carbon cycle models still use the empirically derived remineralization curves of Martin et al. (1987). In this issue, Armstrong et al. (2002) present a quasi-mechanistic model of remineralization to replace the Martin curves. Their analysis is based on a simple model of the US JGOFS EqPac and Arabian Sea sediment-trap data showing that the downward flux of inorganic ballast, composed of dust and siliceous and calcareous shells, largely determines the amount of particulate organic matter that reaches the deep ocean. They also propose two hypotheses for this effect: protection of the organic matter by the ballast (Hedges et al., 2001) and/or organic matter control on the integrity of the sinking particles. Also in this issue, Berelson (2002) analyzed sediment trap data from the US JGOFS EqPac and Arabian Sea sites to estimate particle settling rates. He found that particle sinking rates increase with depth but that this increase is not necessarily correlated with the ratio of organic carbon to mineral content.

3.3. *Regional to global-scale synthesis and modeling*

Regional and basin-scale synthesis and modeling studies (Fig. 2) are exploring the integrated effects of upper ocean ecosystem dynamics and physical circulation. A number of basin and global, three-dimensional coupled biological-physical models developed within the SMP are being used in conjunction with satellite and in-situ observations to investigate the factors governing mean state, seasonal cycle, and interannual variability of the ocean. For example, Christian et al. (2002a) (Pacific regional model) and Gregg (2002) (global model) successfully simulate the large biological signals in the tropical Indo-Pacific associated with ENSO (Chavez et al., 1999). Significant extratropical, interannual variability is also observed in both the SeaWiFS ocean color data and model simulations, though with more mixed model-data skill (Gregg, 2002; Dutkiewicz et al., 2001).

For example, Dutkiewicz et al. (2001) and Follows and Dutkiewicz (2002) found good model-data correspondence in the nutrient limited subtropical North Atlantic, where increased mixing tends to increase biomass, but not in the more light limited subpolar gyre. Pätsch et al. (2002) compare results from a 1-D coupled ecosystem model, which includes both carbon and nitrogen cycling, with data collected at the ESTOC station (European Station for Time Series in the Ocean, Canary Islands). They simulate interannual variability of primary production, air–sea CO_2 exchange, POC export, and rain ratio of particulate matter. The simulations suggest that even low interannual variability in meteorological forcing can produce high interannual variability in carbon fluxes, largely because they alter deep mixing events which provide nutrients to the euphotic zone.

On longer decadal scales, Keller et al. (2002) apply an ocean general circulation model to test whether observed trends in nitrate and apparent oxygen utilization (AOU) in the North Pacific are explicable in terms of the biological pump (i.e., changes in export production or remineralization efficiency) and/or ocean circulation. They conclude that the observed changes in North Pacific intermediate water (based on both GEOSECS and WOCE data) are more likely due to changes in water mass ventilation rates. Sarmiento et al. (in prep.) have organized an intercomparison of existing coupled ocean–atmosphere climate change simulations to quantify the projected changes relevant to marine ecosystems over the next century, which include: warmer, fresher, and lighter surface layers; increased near-surface stratification; and longer growing seasons.

Also clearly evident throughout the SMP is the convergence of data analysis and numerical modeling efforts. This is particularly true with regards to the analysis of the JGOFS/WOCE global CO_2 survey results and global carbon cycle models. A detailed synthesis of the transient tracer, carbonate chemistry and biogeochemically relevant parameters from the global survey is underway (see for example Fig. 2 and http://geoweb.princeton.edu/bigscience/GLODAP/). As described in Lamb et al. (2002) for the Pacific, considerable care has been taken with the global survey carbon system data to create the most consistent and uniform data set as possible. They report a multi-step inter-comparison procedure (which in certain cases, recommends adjustments of specific data sets) using certified reference materials, at-sea replicate analyses, deep-water cross-over points, and hydrographic and internal carbon system consistency. Other SMP and WOCE projects focus on the broader range of global survey data, including hydrography (Johnson et al., 2001), transient tracers, nutrients, and alkalinity as well as issues as such as the internal consistency of the carbonate system variables (Lee et al., 2000a) and the relationship of inorganic carbon concentration to nutrients and temperature (Lee et al., 2000b).

The global survey data provide the comprehensive framework for evaluating large-scale ocean biogeochemical models represented in the SMP through the US and international Ocean Carbon Model Intercomparison Project (OCMIP; http://www.ipsl.jussieu.fr/OCMIP/presentation.html). While not heavily represented in this issue, OCMIP is a key component of the SMP research. A series of model–data and model–model comparisons studies are underway, with early results focusing on CFC (Dutay et al., 2001) and radiocarbon invasion, anthropogenic CO_2 uptake, and the natural biogeochemical carbon cycle. The OCMIP simulations serve as a benchmark for 3-D global carbon cycle model performance and are stimulating a number of sensitivity and model improvement studies (Doney and Hecht, 2001) as groups strive to improve the highlighted model deficiencies and explore new scientific questions. Gnanadesikan and Toggweiler (1999) and Gnanadesikan et al. (2002), for example, demonstrate that relatively weak model vertical exchange (diapycnal mixing) outside of the poles is required to match the ocean silica cycle and the satellite derived export production estimates from Laws et al. (2000).

3.4. Model–data fusion

Other promising directions within the SMP involve the application of model–data fusion, inverse or data assimilation techniques, often borrowed from other fields, to traditional marine biogeochemical problems. For example, non-linear parameter optimization studies are becoming routine for low-dimension ecosystem models (e.g., Evans, 1999; Fennel et al., 2001). Friedrichs (2002) assimilates both in situ EqPac data and SeaWiFS satellite ocean color, using the variational adjoint technique, into a reformulated ecosystem model (Friedrichs and Hofmann, 2001) of the Equatorial Pacific. She successfully retrieves a set of consistent ecosystem model parameters across both El Niño and La Niña periods with two exceptions. The model failures are due to changes in species composition associated with the passage of a tropical instability wave and to a brief period of macro-nutrient limitation during the 1997–1998 El Niño. Data assimilation, while not overcoming inappropriate model dynamics, thus can highlight missing processes and guide future model reformulation.

In other SMP activities, Gruber et al. (2002) import numerical inverse methods developed for atmospheric models to estimate the regional air–sea fluxes of oxygen as well as natural and anthropogenic CO_2. In a complementary study, Robbins and Dickson (pers. comm.) are using physical oceanographic inversion tools to quantify the zonal transport of carbon species within the ocean, which combined with air–sea flux and inventory temporal evolution estimates will allow closure of the large-scale inorganic carbon mass balance.

At a more sophisticated level, full global state estimation efforts are underway (Stammer et al., 2001) that combine historical hydrographic surface forcing and satellite physics data with ocean general circulation models to produce a "best estimate" of large-scale ocean circulation for particular time periods. One of the important lessons from JGOFS is that mesoscale disturbance is ubiquitous in the ocean and has significant ramifications on ocean biogeochemistry. On more regional scales, techniques are being developed for eddy resolving, data assimilation models, for example the work of McGillicuddy and Kosnyrev (2001) simulating the area around the BATS site, which provide the physical context for interpreting and modeling biogeochemical data.

3.5. Future directions

The papers contained in this special issue highlight progress on several fronts to better understand ocean biogeochemistry, and encapsulate that knowledge into numerical models that can then be used to make projections of future behavior. With a few exceptions, the treatment of biology in global biogeochemical models to date has been rather rudimentary. The next step already underway is to combine reasonably sophisticated components for both ecosystem and biogeochemical dynamics within global modeling frameworks. The exact forms of such models are yet to be determined. But based on new insights emerging from JGOFS and other recent field studies, a prototype can be envisioned covering those basic processes that govern surface production, export flux, subsurface remineralization, and the (de)coupling of carbon from macronutrients. Important aspects that need to be addressed include multi-nutrient limitation, size structure and trophic dynamics, plankton geochemical functional groups, microbial loop and dissolved organic matter cycling, subsurface particle transport and remineralization.

Clearly some areas of the field are advancing more rapidly than others, driven primarily by the availability of field observations, and particularly by those data that elucidate the fundamental mechanisms of the system. For example, considerable effort has been devoted to processes governing phytoplankton primary production at a number of levels (e.g., molecular biophysics, cellular physiology, community dynamics, seawater bio-optics and remote sensing). Other areas have received considerably less attention (e.g., phytoplankton loss terms, ecosystem dynamics of the mesopelagic etc.), not because they are considered less important from a carbon cycle perspective, but because the techniques and measurement systems are less advanced. This imbalance is apparent in the construction of present "state of the art" models where some of the parameterizations (e.g., the Martin et al. (1987) particle remineralization curve) are no better than empirical curve fitting.

A major challenge to the oceanographic community is to develop both experimental and modeling approaches that are fundamentally driven by ecological and evolutionary hypotheses. The strong historical links among biological oceanography, organismic biology, and mainstream ecology/evolution studies in the early part of the 20th century (Mills, 1989) have given way to a more "system"-oriented focus. The emphasis is often on chemical and biochemical analyses: phytoplankton treated simply as concentrations of pigments and organic carbon, zooplankton as grazers, and physics as a mechanism for providing nutrients. This oversimplified abstraction, while potentially quite attractive for mathematical representation, cannot serve indefinitely to represent complex biological systems for many diagnostic and prognostic applications. Ultimately we require a better fundamental understanding of pelagic ecosystems to address key questions such as how food webs affect biogeochemical fluxes and how the structure of food webs and corresponding biogeochemical fluxes will change in the coming decades. There also will be increasing pressure to place marine ecological processes within a paeloceanoceangraphic and historical (i.e. evolutionary) context. Achieving this goal, of systematically organizing key biological principles without resorting to myriad autecological (i.e. individual species) studies and anecdotal observations, remains a daunting challenge but one that will be key to the legacy of the JGOFS Synthesis and Modeling Project.

Some important steps that already have been taken in this direction include: (1) recognition of the importance of functional groups of organisms such as diatoms, which cycle $Si(OH)_4$ and are thought to be important in increasing the flux of organic matter from the surface to the abyss, and coccolithophorics which cycle $CaCO_3$; (2) recognition of the important role of micronutrients in shifting the basic structure of the ecosystem and thereby the cycling of biogeochemicals; and (3) recognition that the most abundant phytoplankton in the ocean are the picoplankton, which were only discovered in the past few decades and which are extremely efficient at recycling biogeochemicals within the surface ocean.

The synthesis and modeling component came at the end of the US JGOFS program, and with only a few notable exceptions, numerical models did not strongly influence the planning for the field efforts either in terms of what was measured or how the experiments were designed. In part this reflected the state of the models a decade ago. But much has changed, and future field programs will require a closer, more synergistic relationship between models and observations.

Finally, the success of US JGOFS Synthesis and Modeling Project, while highly dependent upon the creativity and skills of the individual PIs and small-group collaborations, would not be possible without the virtual treasure trove of in situ JGOFS field data and satellite remote sensing products now easily accessible in electronic form. As pointed out by a number of authors in this special volume, their research has been greatly facilitated by, if not made feasible by, the coherent, comprehensive nature of the JGOFS data sets including the time-series, process studies, and global survey. The timely, public release of data (and models/simulations) and explicit support of data management (which is neither glamorous nor cheap) are major cultural and programmatic advances for our field, lessons that should not be neglected in the future.

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